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A Numerical Study of the Effect of the Gulf Stream and the Appalachian Mountains on Carolina Coastal Frontogenesis

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13. ABSTRACT (*Maximum 200 words*)

Three numerical experiments were conducted to understand the role of the Gulf Stream and the Appalachian mountains on the formation of coastal frontogenesis along the mid-Atlantic coast during the winter months. A 3-dimensional, 10-layer, 1-way interactive, triple-nested hydrostatic model was used. The model physics includes dry convective adjustment, explicit large-scale precipitation, parameterized convective-scale circulations, and parameterized boundary layer physics using a similarity theory formulation. Initial conditions for the numerical model are obtained from the Second Intensive Observation Period (IOP-2) of the Genesis of Atlantic Lows Experiment (GALE).

Results of the numerical experiments show that the Gulf Stream plays a significant role in developing coastal frontogenesis through transfer of large amounts of sensible and latent heats to the cold, dry atmospheric air of Arctic origin. The Gulf Stream is also found to be crucial in producing convective precipitation along the Carolina coast. On the other hand, the Appalachian mountains, which are responsible for cold air damming, are found to play only a minor role in the coastal frontogenesis.

14. SUBJECT TERMS

Appalachian Mountains; Boundary layer physics; GALE; Scale precipitation; IOP-2; Cold air damming; Parameterized convective scale circulation

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CONTENTS

A NUMERICAL STUDY OF THE EFFECT OF THE GULF STREAM AND THE APPALACHIAN MOUNTAINS ON CAROLINA COASTAL FRONTOGENESIS

INTRODUCTION

The Carolina coastal front, which is often observed during winter, is a shallow mesoscale phenomenon that separates the warm, moist oceanic air mass from the cold, dry continental air mass. It is marked by a large thermal contrast and cyclonic shear. Based on east coast cyclone climatology, the coastal front has been shown to play a key role in the genesis of the offshore cyclones [1,2]. Reference 3 hypothesized that the cyclogenesis is essentially the result of interaction between the low-level positive Isentropic Potential Vorticity (IPV) anomaly and an upper-level one. The coastal front can provide the needed low-level positive IPV anomaly to trigger the cyclogenesis. The coastal frontogenesis has a great impact on the local weather as well as on regional weather. Because of the key role in offshore cyclogenesis, it is important to understand the external forces that create the coastal frontogenesis.

Several observational, theoretical, and numerical studies have been made in the last few decades to improve our understanding of these coastal fronts (the Gulf coast of Texas [4], the New England coast [5-10], and the Carolina coast [11-17]). Two unique processes frequently observed along the mid-Atlantic coastal region are cold-air damming by the Appalachian mountains and the transfer of large amounts of sensible and latent heat fluxes from the warm Gulf Stream. These result from the presence of the Appalachian mountains, which are located west of the coast, and the Gulf Stream, which flows to the east.

In cold-air damming, the Arctic cold dry air flows northeasterly and is channeled along the Appalachian mountains, which act as a physical barrier to dam the cold, dry air mass to the east. This creates a narrow, inverted, sea-level-pressure (SLP) ridge.

Studies have suggested that cold-air damming by the Appalachian mountains may be a cause of coastal frontogenesis. For example, Refs. 5 and 6 documented the existence of the narrow inverted SLP ridge in conjunction with the New England coastal frontogenesis; they indicated that cold-air damming by the northern Appalachian mountains is one of the mechanisms causing frontogenesis. Reference 18 suggested that cold-air damming, which contributes to a land-sea temperature contrast in excess of the wintertime climatological value of 2-3 °C per 100 km, may cause the frontogenesis. Based on numerical experiments, Ref. 8 concluded that the presence of mountains did not have a significant effect on New England frontogenesis. However, it is not clear what role cold-air damming plays in the Carolina coastal frontogenesis.

The Gulf Stream is a warm ocean current observed off the east coast of the United States. Its core temperature is about 25 °C year around. The mean width of the Gulf Stream is roughly 100 km, and it can meander 50 km within 1 week. The temperature difference between the Gulf Stream and the

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air above can be as large as 20 °C during a cold air outbreak [19]. Some of the highest wintertime energy transfers from the ocean to the atmosphere takes place over the Gulf Stream region of the Carolina coast [20-22]. Sharp horizontal temperature gradients between the coast and the Gulf Stream play a significant role in the frontogenetic processes [15,16,23,24].

A triple-nested version of the Naval Research Laboratory (NRL) mesoscale model is used to study mesoscale coastal processes during the coastal front formation of the Genesis of Atlantic Lows Experiment, Second Intensive Observation Period (GALE IOP-2). The use of a nested model provides better lateral boundary conditions for the regions of interest. Three numerical sensitivity experiments investigated the role of the Gulf Stream and the Appalachian mountains on the mesoscale circulations and convective precipitation along the Carolina coast.

The synoptic setting of the coastal frontogenesis event during the GALE IOP-2 is described. A brief description of the triple-nested version of the NRL mesoscale model is followed by a description of the model domain and the data set used for this study. The experiment designs along with a discussion of the results and a summary and conclusions are given.

REVIEW OF THE SYNOPTIC SITUATION

Following a cold front passage over the mid-Atlantic region on 23 January 1986, an intense anticyclone developed over central Canada. During the next 24 hours the anticyclone intensified as it moved toward the coast. By 1200 UTC 25 January 1986, the center of the anticyclone was located over eastern Canada. Surface winds over the Atlantic ocean and offshore of the east coast of the United States were mostly easterly. The westward-moving cold, dry air mass of Arctic origin was modified by the relatively warmer Gulf Stream into a warm and moist air mass. During this time, cold air was trapped by the Appalachian mountains, creating an inverted ridge. The inverted SLP ridge is believed to be the result of the wedge of entrenched cold air to the east of the Appalachian mountains; the inverted trough was over the Gulf Stream front [16]. The coastal front was rather disorganized at this time. The anticyclone continually propagated eastward, providing an easterly wind over the Gulf Stream and bringing modified warm and moist air to coastal regions of the Carolinas by 0000 UTC 26 1986. The inverted SLP ridge was still located east of the Appalachian mountains while the intensity of the inverted ridge became weaker. On the other hand, the inverted SLP trough intensified and the low SLP zone extended to a larger area along the coast. Reference 16 provides a mesoscale analysis of this synoptic situation.

MODEL AND DATA

The numerical model used in this study is a 10-layer version of the NRL mesoscale model. The model is based on primitive equations in a terrain following a σ ($=p/p_s$) vertical coordinate. The finite-difference form of the differential equations is second-order accurate on a staggered C-grid in the horizontal direction [25]. In the vertical direction, the model domain is divided into 10 layers of equal thickness in the σ coordinate.

Model physics includes dry convective adjustment and latent heat released due to convective and nonconvective precipitation. The atmospheric radiative transfer processes are not included in this version because of the short 24-h integration period. Convective heating, precipitation, and moistening of the environment are parameterized by using the method developed in Ref. 26 and modified according to Ref. 27. The large-scale or nonconvective precipitation/heating occurs when saturation is reached on the resolvable scale. Part of the excess moisture is assumed to precipitate into the lower model layer and to re-evaporate by a factor that depends on the height at which the

saturation occurs. The rest of the excess moisture precipitates to the ground. Exchange of sensible heat, latent heat, and momentum fluxes between the boundary layer air and the underlying surface are parameterized, using a generalized similarity theory in which the drag coefficients are stability dependent [28].

Unrealistic lateral boundary conditions are believed to be a major source of error in regional primitive equation models because of the ill-posed mathematical nature of the problem [29]. One option to reduce the error in lateral boundary conditions is using the 1-way nesting technique. The model has three nests: the outer nest with coarse resolution, the middle nest with medium resolution, and the inner nest with fine resolution. Boundary conditions for the two inner nests are obtained from the immediate coarser nest through interpolation in time and space at every time step. Boundary conditions for the coarser nest are obtained from the National Meteorological Center/Regional Analysis and Forecasting System (NMC/RAFS) at synoptic times through interpolation.

Figure 1 illustrates the model domain used in this study: the outer nest covers the North American continent and the adjacent oceans and extends from 40° to 140°W and 10° to 70°N, with a horizontal resolution of 2° longitude (170 km at 40°N) by 1.5° latitude (166.5 km); the middle nest covers the eastern part of the US and extends from 60° to 100°W and 23.5° to 50.5°N, with a horizontal resolution of 2/3° longitude (56.7 km at 40°N by 1.5/3° latitude (55.5 km). The inner nest covers the Carolinas and the Gulf Stream and extends from 70° to 90°W and 32° to 40°N, with a horizontal resolution of 2/9° longitude (18.9 km at 40°N) by 1.5/9° latitude (18.5 km). With this grid resolution, the integration time step used is 450 s on the outer grid, 150 s on the middle grid, and 50 s on the inner grid.

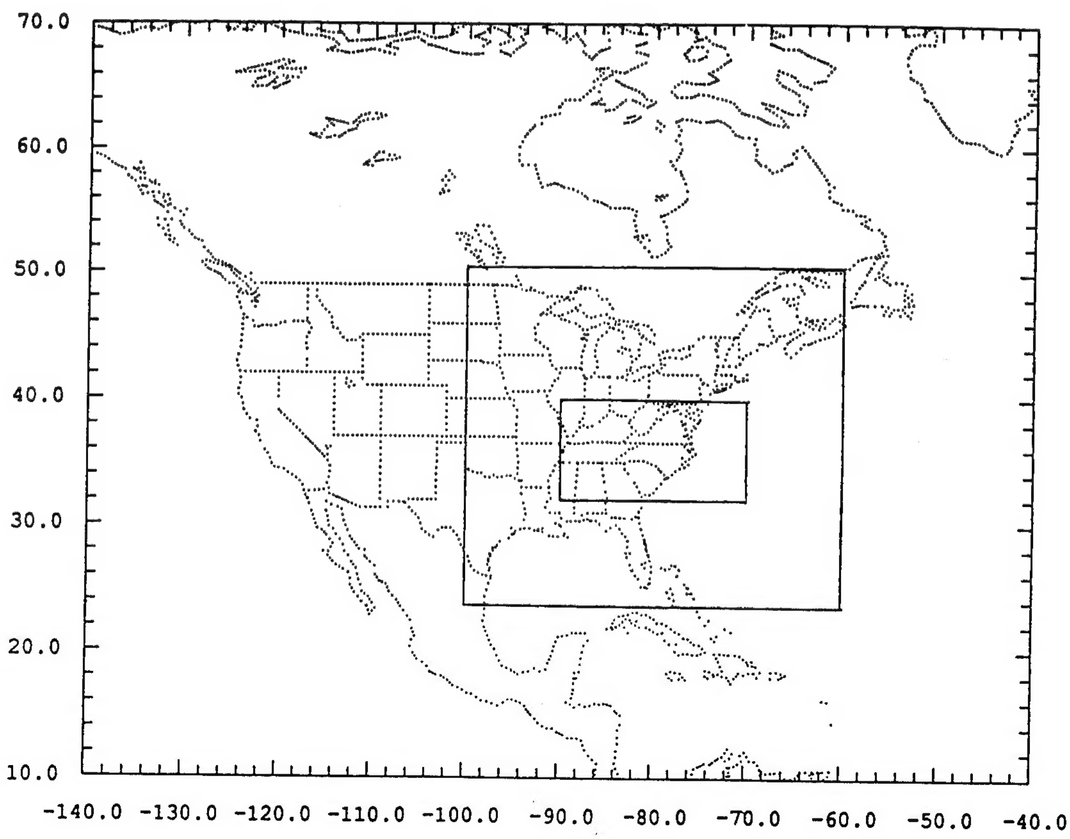


Fig. 1 — Model domain used in this study

Because one of the objectives of this study is to examine the importance of the Gulf Stream on the coastal frontogenesis, high-resolution SST data are required. To represent the Gulf Stream more realistically, the SST analysis of 14-km resolution provided by NOAA, taken from the GALE data sets, was interpolated directly to the inner nest. Because the high-resolution SST data were available only for the GALE region, the SST data used in both the outer and middle nests were obtained from an analysis that merged the weekly mean and the coarse SST observations. Figure 2 shows the SST fields for the inner nest. Sea/ice boundary was derived from the US Navy's climatological sea/ice boundaries for month of January. The topography data used in the model was directly created by interpolating the US Navy's 10 × 10-min database. Figure 3 shows model topography for the inner nest. Mountains shown in this figure are the Appalachian mountains.

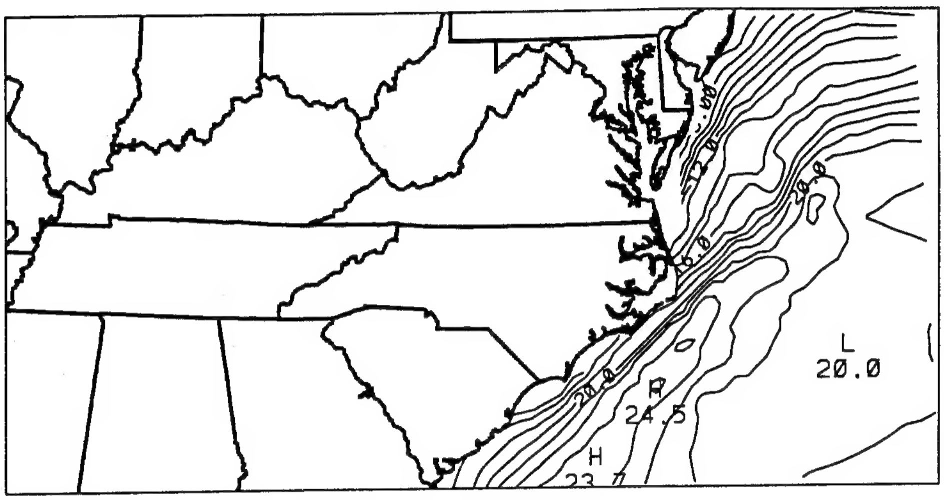


Fig. 2 — The SST analysis for the inner nest based on 14-km resolution SST provided by NOAA

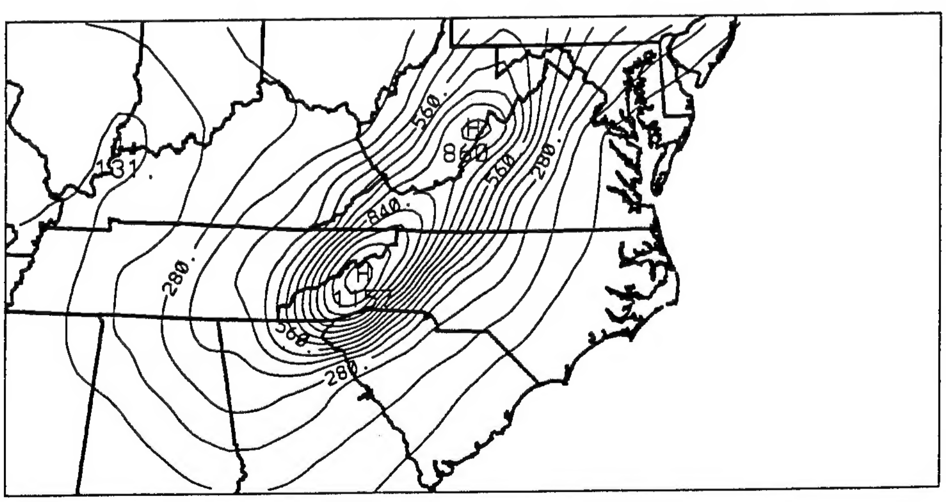


Fig. 3 — Terrain height for the inner nest interpolated from the US Navy's 10 × 10-min database

The basic meteorological dataset used for the initial conditions was obtained through horizontal and vertical interpolation from the NMC/RAFS 2.5° hemispheric analysis (without enhanced GALE data). The vertical normal mode initialization scheme of Ref. 30, as applied by Ref. 31, was then used to reduce the amplitude of spurious gravity wave oscillations that result during the numerical integration of the model. References 28 and 31 provide detailed discussion of the model design, physics, and initialization.

DISCUSSION

The main objectives of this study were to understand the impact of the Gulf Stream and the Appalachian mountains on mesoscale circulations along the east coast of the United States. To achieve these objectives, three numerical experiments were performed. The first numerical experiment was designed to simulate the coastal frontogenesis and related mesoscale features resulting from the Appalachian mountains and the Gulf Stream. This is considered the control experiment. Two more experiments were conducted to determine the effect of the Gulf Stream and of the Appalachian mountains on the coastal frontogenesis. The following is a brief description of the three numerical experiments.

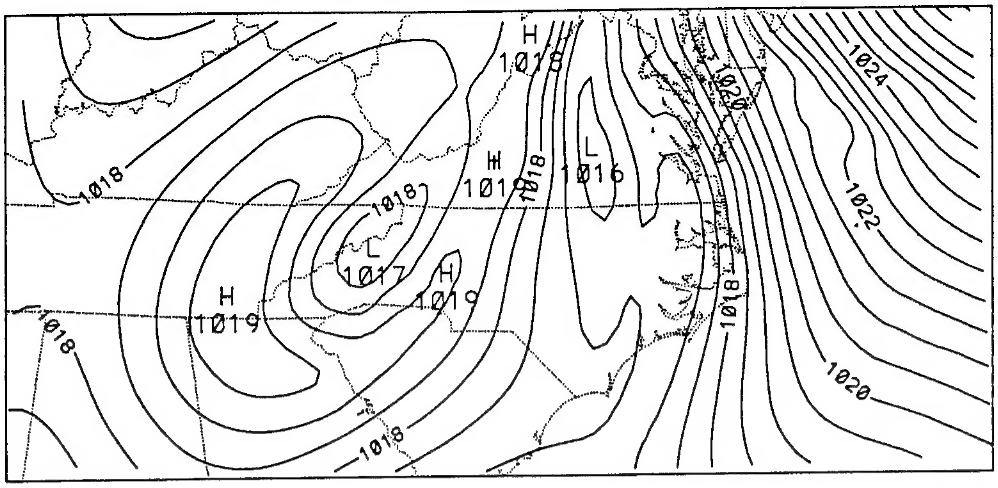
Experiment 1 (EXP1): The purpose of this experiment was to reproduce the coastal frontogenesis event that took place along the Carolina coast during the GALE IOP-2. The external forces are due to both the Gulf Stream and the Appalachian mountains.

Experiment 2 (EXP2): The purpose of this experiment was to investigate the role of the Gulf Stream on the formation of the Carolina coastal frontogenesis. The warm core of the Gulf Stream sea surface temperature (SST) offshore of the Carolinas is about 25°C year around. On the other hand, the SST of the shelf water, which is not affected by the Gulf Stream, is about 6°C during winter. The Gulf Stream transports a large amount of energy from lower latitudes. Because of the warm SST over the Gulf Stream, an appreciable amount of turbulent sensible and latent heat fluxes to the atmosphere occurs. If the Gulf Stream did not exist, the SST offshore of the Atlantic coast would be approximately the same as the SST of the shelf water, which was about 6°C during the period of the experiment. For simplicity yet without losing generality, values of SST larger than 6°C are set equal to 6°C to eliminate the existence of the Gulf Stream in the model. The impact of the Gulf Stream on coastal mesoscale processes is then examined by comparing the results from the EXP2 with the one from the EXP1.

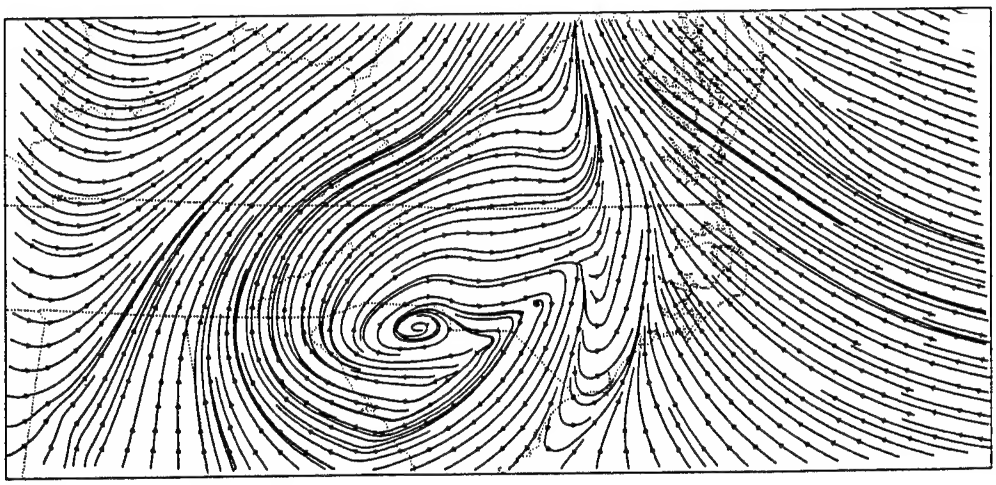
Experiment 3 (EXP3): The purpose of this experiment was to investigate the effects of the Appalachian mountains on the Carolina coastal frontogenesis and associated mesoscale features. An interesting mesoscale feature is the cold-air damming east of the Appalachian mountains during the coastal front events. The cold-air damming is due to the mechanical blocking of the Appalachian mountains under favorable synoptic conditions. The cold-air damming by the Appalachian mountains can create and enhance the lower level atmospheric thermal contrast between land air and oceanic air. However, it is not quite clear how important cold-air damming is in coastal frontogenesis processes. To eliminate the mountain, the terrain height is set to zero everywhere in the model domain.

EXP1 (Control Experiment)

Figure 4 is the simulation from EXP1 valid at 0000 UTC 26 January 1986 for the inner nest. Figure 4(a) shows the simulated SLP. It shows that pressure values less than 1017 mb covers the eastern part of the Carolinas and Virginia, with a mesolow of 1016 mb located at south central



(a) Simulated SLP

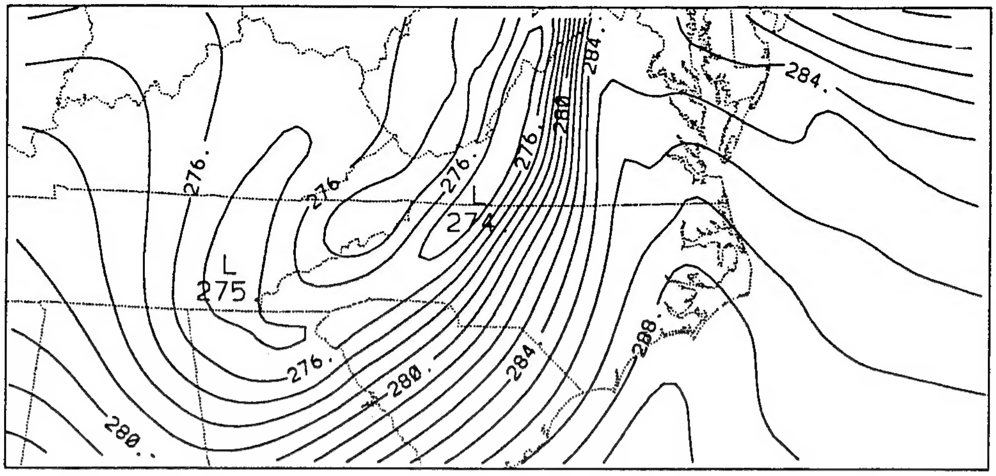


(b) Streamlines at 1000 mb

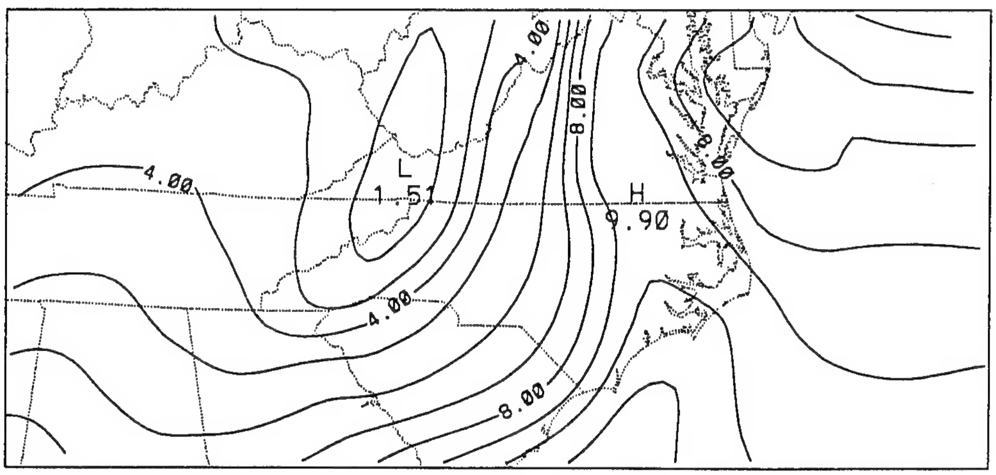
Fig. 4 — 24-h simulation from EXP1

Virginia. Surface pressure increases toward the mountain. The simulated SLP reasonably reproduced the observed narrow surface high-pressure ridge east of the Appalachian mountains and the inverted trough along the Carolina coast. Figure 4(b) is the simulated 24-h streamline field at 1000 mb. The convergence zone along the cyclonic coastal front is well simulated. The model also reproduces the observed northerly wind near the coastal areas of the Carolinas.

Figure 5(a) shows simulated 24-h temperatures at 950 mb. The model simulated the cold-air damming by the Appalachian mountains. Low-level air flow around the mountain can also be seen. Also seen in Fig. 5(a) is an inverted surface ridge east of the mountain caused by cold-air damming. The presence of a warm temperature zone from the Carolina coast to the coastal Virginia coincides with the low pressure zone (Fig. 4(a)). Figure 5(b) is the simulated mixing ratio at 950 mb. The effect of warm air advection by southeasterly wind can be seen along the coastal regions of the Carolinas and Virginia. Mixing ratios in this region are larger than 9.0 (gkg^{-1}).



(a) Temperature in degree K

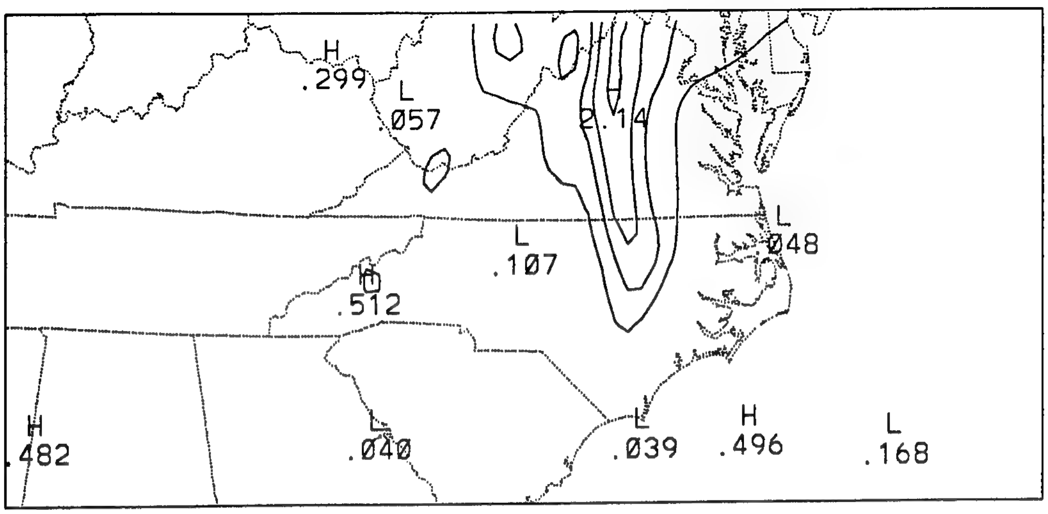


(b) Mixing ratio in gkg^{-1}

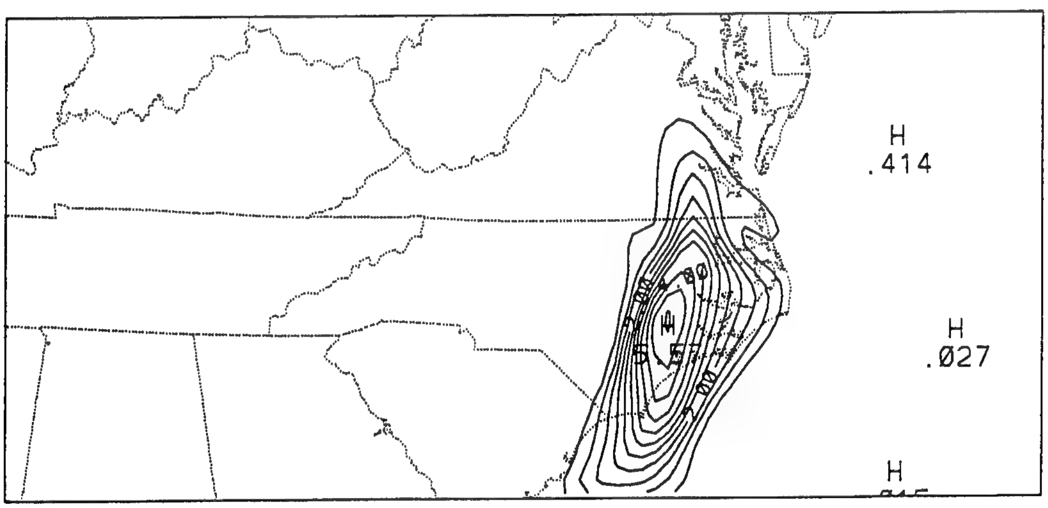
Fig. 5 — 24-h simulation from the EXP1 at 950 mb

Figure 6 shows the accumulated 24-h precipitation. The nonconvective large scale precipitation, with a maximum value exceeding 2 cm [Fig. 6(a)], covers most of Virginia. Convective precipitation with a maximum value over 5 cm occurs over the Carolina coast [Fig. 6(b)].

The simulated 24-h vertical velocity at 850 mb [Fig. 7(a)] shows an upward motion along the Carolina and Virginia coasts, with a maximum vertical velocity of about 26 cm/s over northern North Carolina. However, as can be seen in Fig. 7(a), the location of the maximum precipitation [Fig. 6(b)] is to the south of the region for two reasons. One is that the availability of moisture is greater near the coast. Frictional convergence near the coast could be another reason. To investigate the vertical structure of the upward motion, Fig, 7(b) shows an east-west cross section of the simulated 24-h vertical velocity at 36°N. The center of the upward motion is located at 700 mb and has a magnitude of 28 cm/s. The vertical motion is narrow near the coast and sharply defined. Precipitation occurs as the warm, moist air is lifted over the cold air dome east of the Appalachian mountains.

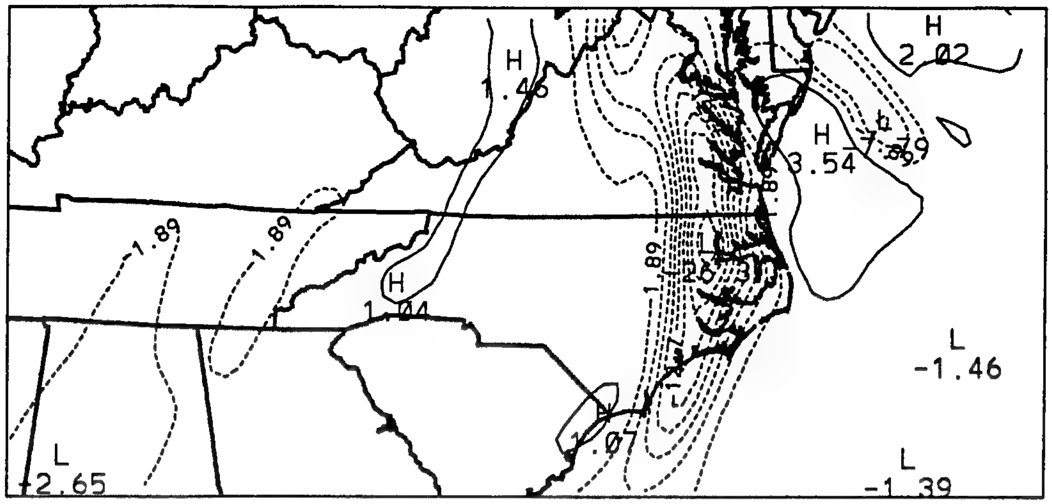


(a) Nonconvective precipitation

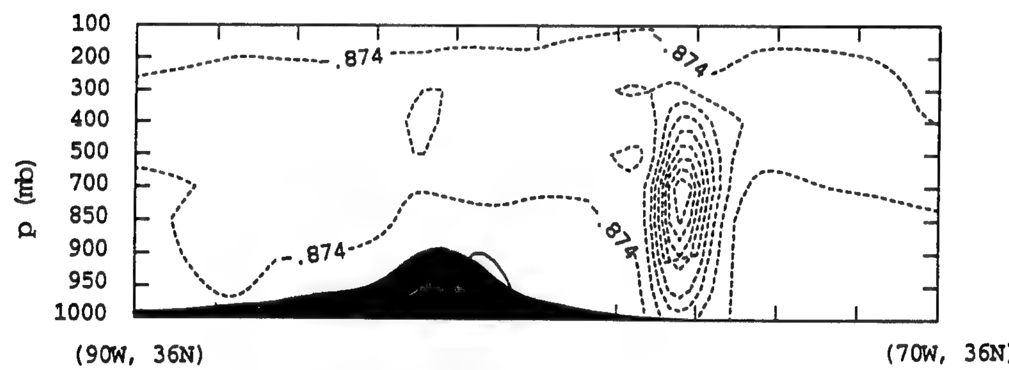


(b) Convective precipitation

Fig. 6 — 24-h accumulated precipitation from the EXP1



(a) At 850 mb

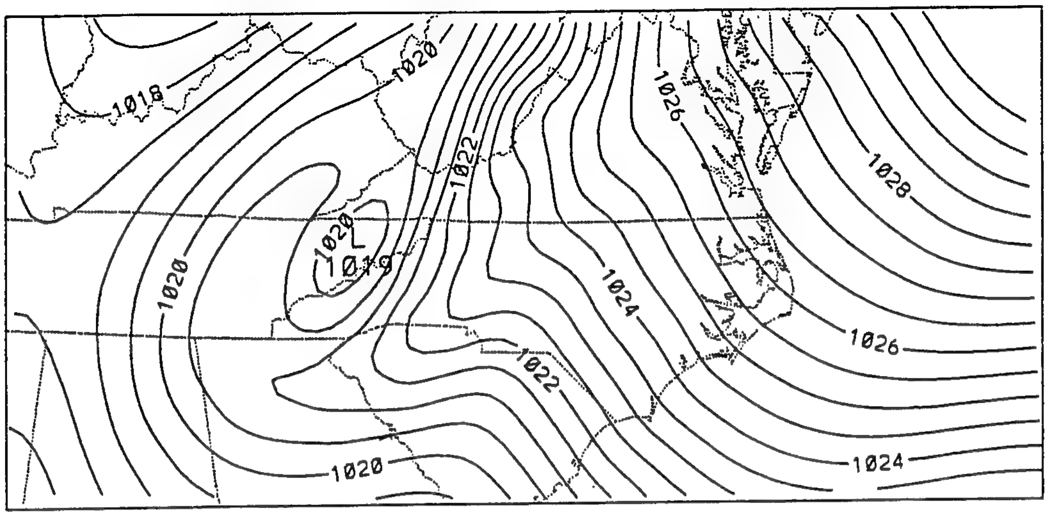


(b) East-west cross section at 36°N

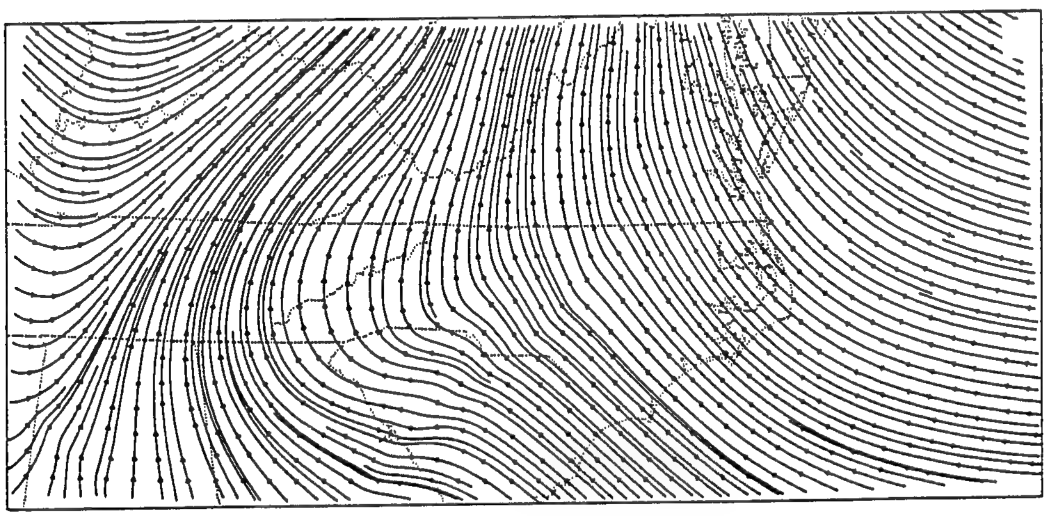
Fig. 7 — Simulated 24-h vertical velocity (in cm/s) from EXP1 for the inner nest

EXP2 (Effect of the Gulf Stream)

Figure 8 presents the 24-h simulation from EXP2 valid 0000 UTC on 26 January 1986 for the inner nest. Figure 8(a) shows the simulated SLP. With the Gulf Stream removed from the model, the coastal front is missing in the simulation although cold-air damming by the Appalachian mountains is present. We can see that the SLP distribution over the western half of the model domain is very similar to the one from the control experiment. However, SLP distributions along the Carolina coast and eastern Virginia are quite different from EXP1 [Fig. 4(a)]. The inverted trough along the Carolina coast and eastern Virginia is absent in the model simulation. The inverted ridge east of the Appalachian mountains has been enhanced significantly (by about 4 mb). An increase in SLP by about 9 mb is found near the coastal regions as compared to EXP1. The increases in SLP are mainly caused by the colder temperature in the simulation. Figure 8(b) is the simulated 24-h streamline field at 1000 mb. The cyclonic coastal front convergence zone is not present in this simulation.



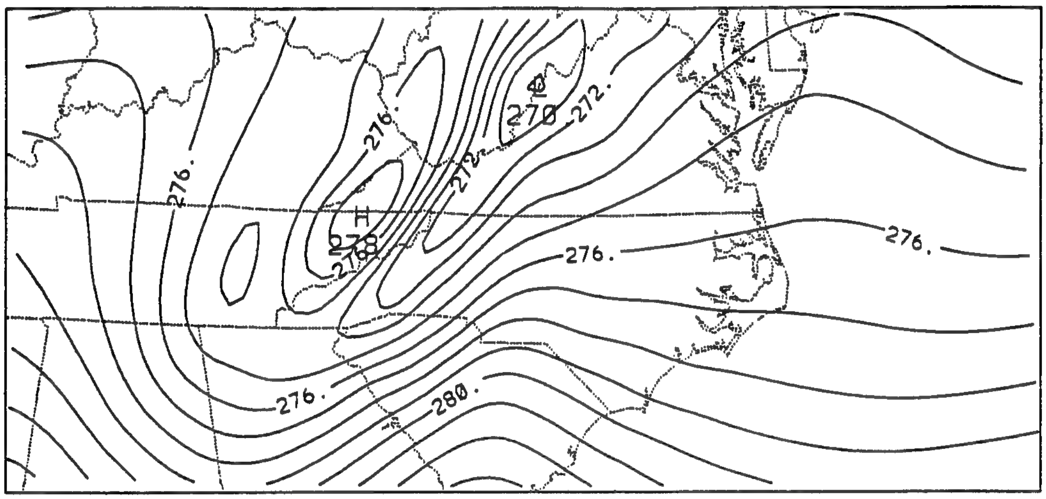
(a) Simulated SLP



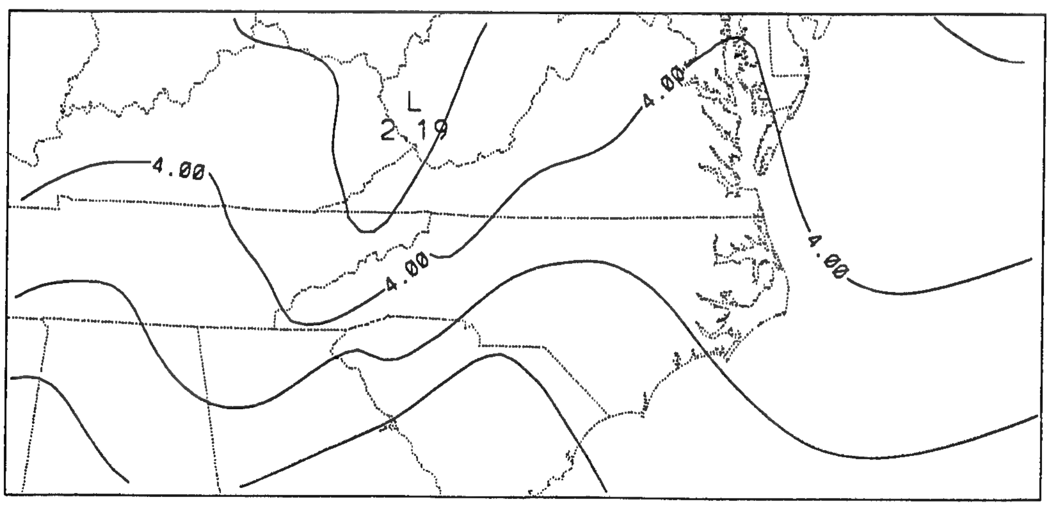
(b) Streamlines at 1000 mb

Fig. 8 — 24-h simulation from EXP2

Figures 9 shows the simulated 24-h temperatures and the mixing ratios at 950 mb for the EXP2, respectively. Figure 9(a) shows a much colder air mass over the eastern half of the model domain as compared to the simulation from the EXP1. The air temperature at 950 mb along the Carolina coast and the eastern part of Virginia is about 10°C colder as compared to EXP1. Note that the existence of the Gulf Stream affects not only the temperature field, but also influences the moisture field at 950 mb. The mixing ratio differences at 950 mb between EXP1 and EXP2 suggest that the air mass at 950 mb [Fig. 9(b)] is about 50% drier over the Carolina coastal region when the Gulf Stream is not present. As a consequence of less latent and sensible heat fluxes into the atmosphere, the simulated precipitation and its area coverage are greatly reduced in the eastern half of the model domain.



(a) Temperature in degree K



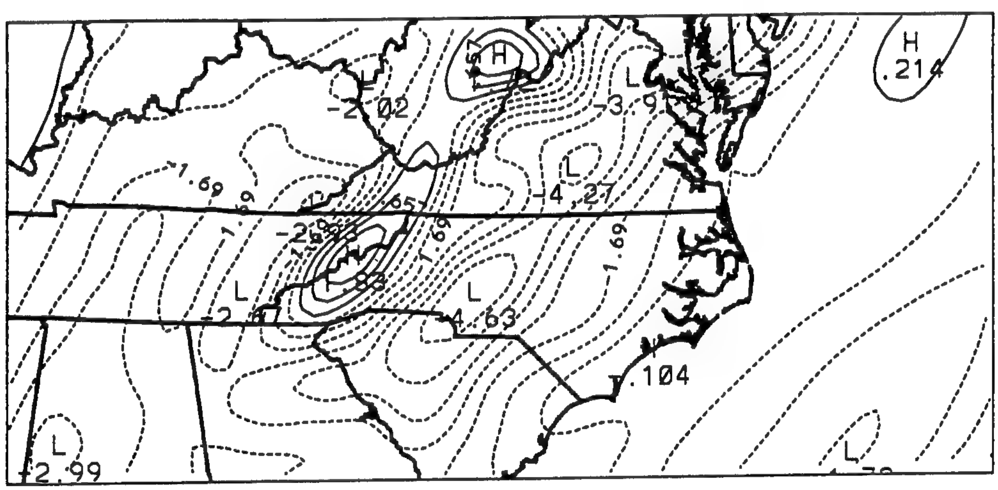
(b) Mixing ratio in gkg^{-1}

Fig. 9 — 24-h simulation at 950 mb from the EXP2

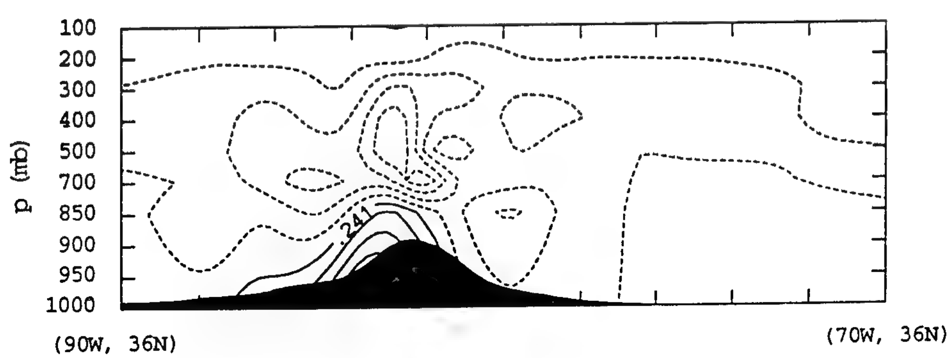
The convective precipitation does not exist in the EXP2 simulation, and the maximum value of nonconvective precipitation is reduced by more than 60% as compared to the EXP1. Simulated 24-h vertical velocities at 850 mb are shown in Fig. 10(a). The magnitudes of the vertical velocities near the coastal region are much smaller (about 3 cm/s) compared to the ones in the EXP1 [Fig. 7(a)]. There is an upward motion east of the mountains and a downward motion in west caused by the southeasterly flow over the mountains. In EXP1, flow over the mountains was absent because of the cold-air damming. Figure 10(b) is an east-west cross section of the simulated 24-h vertical velocities at 36°N. Most of the vertical motions are near the mountains. Upward motion near the coast for this case is drastically reduced as compared to the case with the Gulf Stream (EXP1). Because of the reduction in moisture availability in the lower atmosphere and weaker upward motions, convective precipitation is totally absent in the EXP2.

EXP3 (Effect of the Appalachian Mountains)

Figure 11 is a 24-h simulation from EXP3 valid at 0000 UTC 26 January 1986 for the inner nest. Figure 11(a) shows the simulated 24-h SLP. The model predicted a much broader ridge over the mountain region and a broader trough over the coastal region as compared to EXP1. Figure 11(b) is the simulated 24-h streamlines at 1000 mb. The streamlines display a cyclonic convergence along the coastal areas and a coastal front is present.

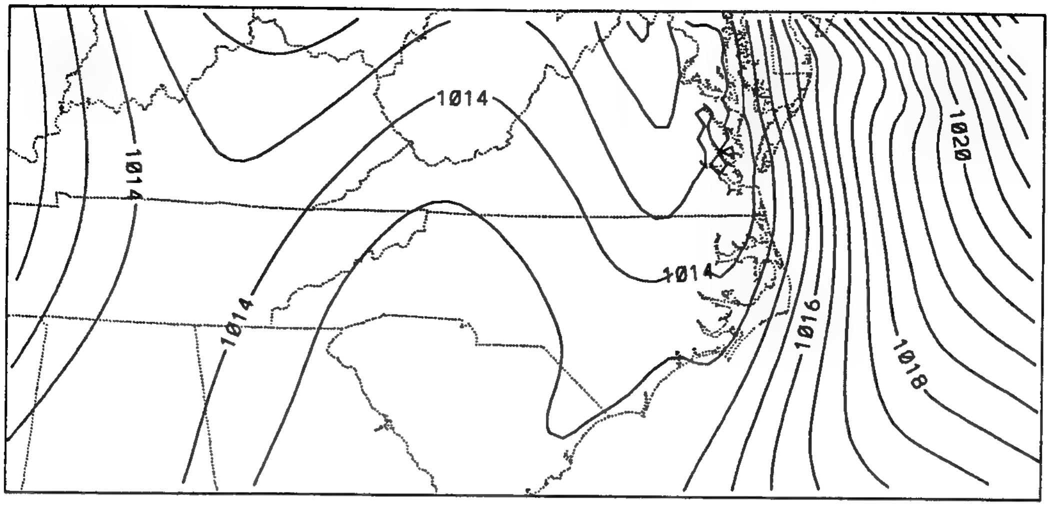


(a) At 850 mb

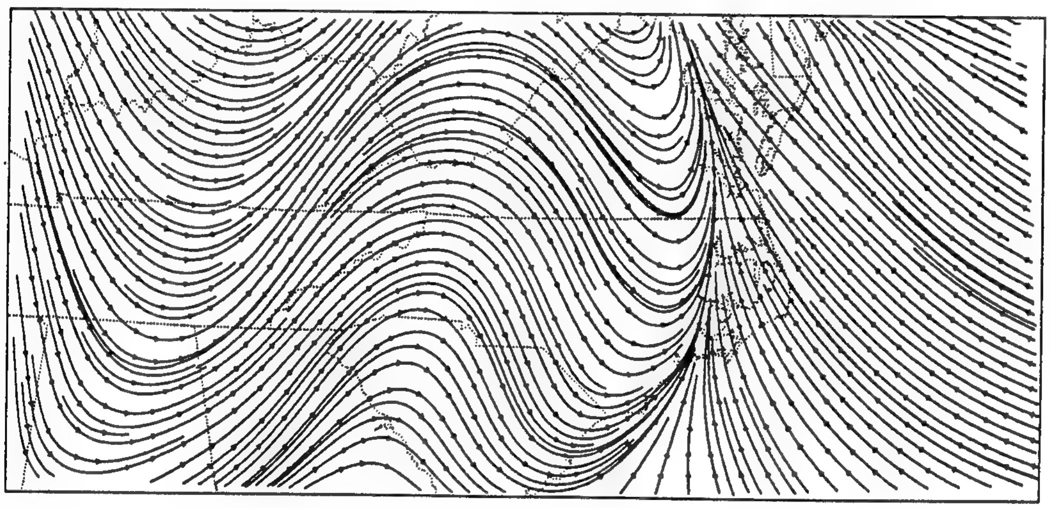


(b) East-west cross section at 36°N

Fig. 10 — Simulated 24-h vertical velocity (in cm/s) from EXP2



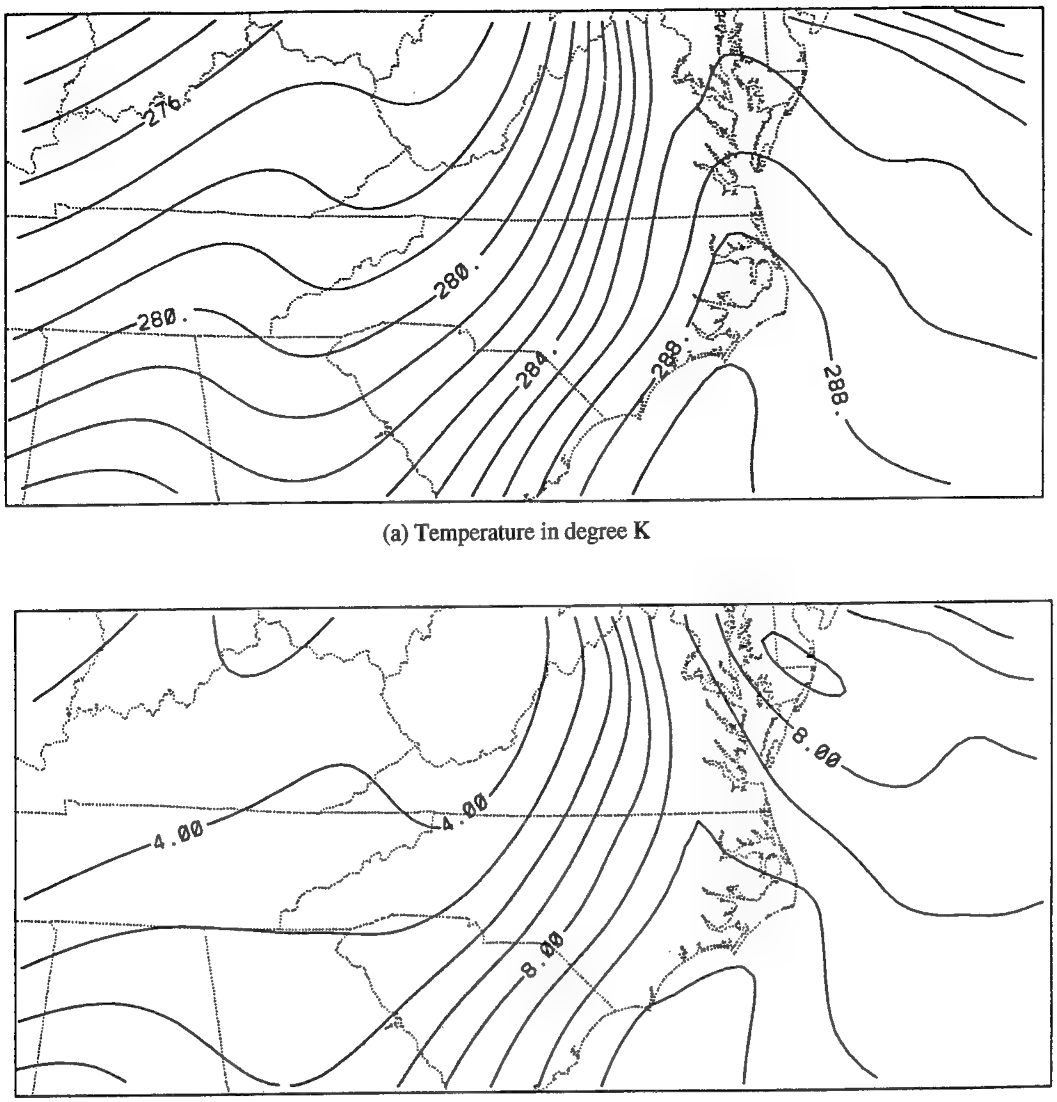
(a) Simulated SLP



(b) Streamlines at 1000 mb

Fig. 11 — 24-h simulation from EXP3

Figure 12(a) shows the simulated 24-h temperature at 950 mb from EXP3. Without the topography, the cold-air damming does not exist. This is reflected by the absence of the cold-air belt east of the Appalachian mountains. Without the mountains, the warm air modified by the Gulf Stream is able to move more inland. A closer examination of the temperature distribution between EXP1 and EXP3 at 950 mb reveals a warmer temperature of more than 4°C inland for the EXP3. This difference occurs in the region where the Appalachian mountains are present. Negligible temperature difference occurred over the coastal regions. Figure 12(b) is the simulated 24-h moisture field at 950 mb for EXP3. The moisture distribution displays a pattern similar to EXP1 [Fig. 4(b)]. However, without the topography, the moist air is able to penetrate farther inland, but the moisture gradient inland is weaker. The weaker horizontal temperature and moisture gradients caused a broader and weaker coastal front. Consequently the model predicted a weaker but broader precipitation along the front.



(a) Temperature in degree K

(b) The mixing ratio in gkg^{-1}

Fig. 12 — 24-h simulation from EXP2 at 950 mb

Figure 13 shows the 24-h accumulated convective precipitation. The convective precipitation is over a much broader area, which now covers eastern parts of both North Carolina and Virginia. In EXP1, convective precipitation was mainly over the Carolina coast. For EXP3, with the mountain removed the maximum convective precipitation has decreased by about 40%. The results show a weaker, nonconvective large-scale precipitation pattern as well. The simulated 24-h vertical velocity at 850 mb [Fig. 14(a)] indicates upward motion along the Carolina and Virginia coast similar to the EXP1. However, the maximum value of the vertical velocity is now only 22 cm/s and is located over the Virginia coast. To examine the vertical structure of the upward motion, an east-west cross section of the simulated 24-h vertical velocity at 36°N was analyzed. The center of the vertical motion, with a value of about 15 cm/s is located at 850 mb and is much broader and weaker compared to the one in EXP1 [Fig. 7(b)]. Without the mountains, cold-air damming is absent, and the uplift of the air parcels is weaker. With a broader and weaker vertical motion, the simulated convective precipitation covered a larger area, with the maximum value reduced by about 40% as compared to the EXP1.

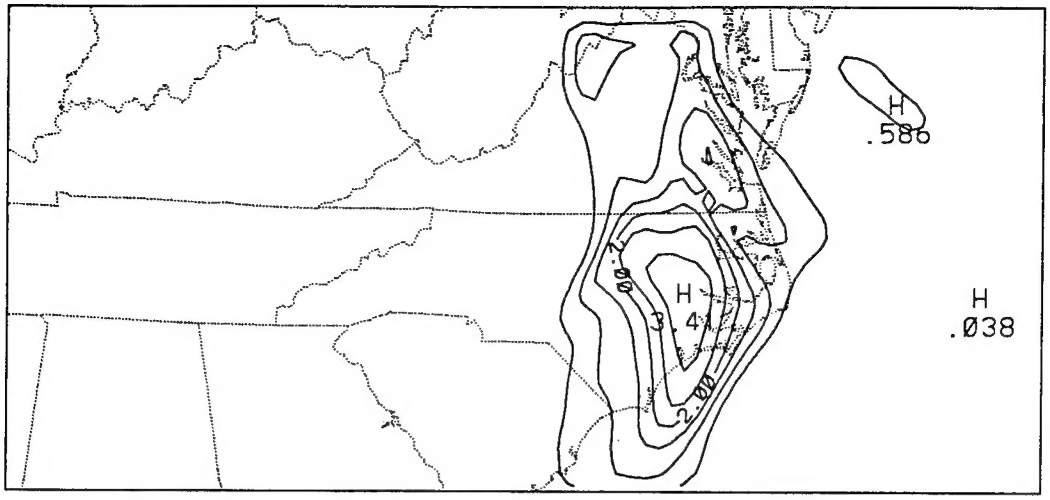
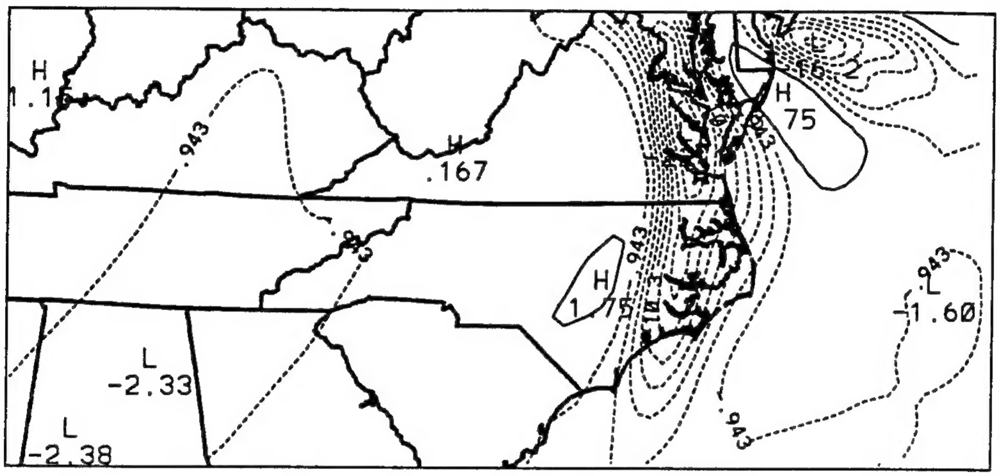
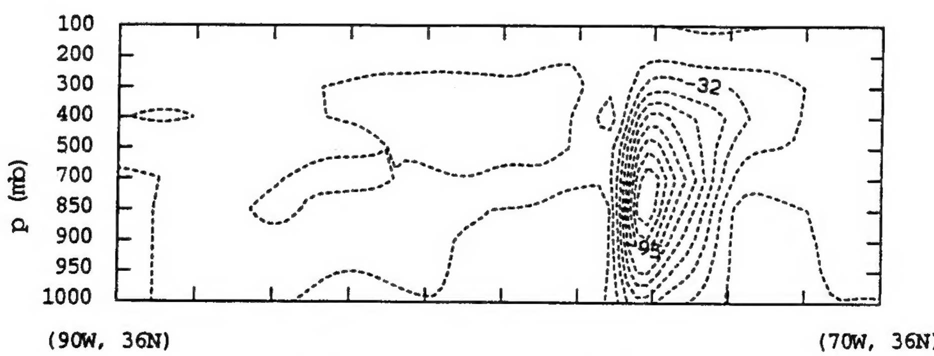


Fig. 13 — 24-h accumulated convective precipitation (cm) from EXP3



(a) At 850 mb



(b) East-west cross section at 36°N.

Fig. 14 — Simulated 24-h vertical velocity (in cm/s) from EXP3 for the inner nest

The most important effect of the Appalachian mountains is to block the cold air on the east side. This cold-air damming plays a significant role in forming the observed inverted ridge east of the Appalachian mountains. The inclusion of the Appalachian mountains allows the model to simulate a stronger horizontal temperature and moisture gradient, which then leads to more realistic precipitation forecast.

SUMMARY AND CONCLUSIONS

Three numerical experiments were conducted to understand the role of Gulf Stream thermal forcing and cold-air damming resulting from the Appalachian mountains on coastal frontogenesis. The model used in this study is a triple-nested version of the NRL mesoscale numerical model based on primitive equations. The model resolutions are approximately 180, 60, and 20 km for the outer, middle, and inner nests, respectively. A vertical normal-mode initialization procedure was used to get the initial data for each of the three experiments.

The model simulated the observed cold-air damming, the inverted ridge east of the Appalachian mountains, inverted trough along the Carolina coast, and the Carolina coastal frontogenesis. The Gulf Stream is found to play a significant role in coastal frontogenesis. The Gulf Stream enhances the low-level horizontal temperature and moisture gradients. The presence of the Gulf Stream is found to be important in producing precipitation along the Carolina coast. Without the Gulf Stream, the coastal front, convective precipitation will be absent and nonconvective precipitation will be greatly reduced. The Appalachian mountains play a secondary role in forming the coastal front. The mountains are responsible for the observed cold-air damming and they also prevent the penetration of moist air further inland. Without the mountains, the simulated coastal front is broader and weaker. As a consequence, the convective precipitation covered a broader area and the maximum value of precipitation decreased by 40%.

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